

Long baseline neutrino oscillation experiments

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Abstract. Evidences for neutrino oscillations coming from atmospheric and solar observations can be probed by terrestrial long baseline experiments. This requires accelerator beams or nuclear power plants. The current status of these searches as well as future activities are discussed. A precise determination of all matrix elements and searches for a leptonic CP-violation will be possible with high intensity accelerator beams currently discussed in the context of neutrino factories.

1 Introduction

A non-vanishing rest mass of the neutrino has far reaching consequences from cosmology down to particle physics. For recent reviews see [1,2]. In the last years growing evidence for such a mass arose in neutrino oscillation experiments. In a simple two flavour mixing scheme the oscillation probability P is given by

$$P(L/E) = \sin^2 2\theta \sin^2(1.27 \Delta m^2_{ij} L/E) \quad (1)$$

with $\Delta m^2_{ij} = |m_j^2 - m_i^2|$, L the source-detector distance and E the neutrino energy. The first evidence comes from the LSND-experiment [3], observing an effect in the $\bar{\nu}_\mu - \bar{\nu}_e$ channel. However a large fraction of the possible parameters are in contradiction with other experiments especially KARMEN [4] and also for $\Delta m^2 > 10 \text{ eV}^2$ with NOMAD [5]. The most likely parameter sets are $\Delta m^2 \approx 1 \text{ eV}^2$ and mixing angles about $\sin^2 2\theta \approx 10^{-3}$, see also the results from a combined data analysis [6]. The second evidence is coming from the zenith angle distribution of atmospheric neutrinos as observed by Super-Kamiokande, showing a clear deficit in upward going ν_μ neutrinos [7] meanwhile confirmed by other experiments [8,9]. For Super-Kamiokande it can be explained by oscillations with Δm^2 in the range $1.6 - 4 \cdot 10^{-3} \text{ eV}^2$ and $\sin^2 2\theta > 0.89$ (90 % CL) assuming $\nu_\mu - \nu_\tau$ transitions. Last not least there is the long standing solar neutrino problem, which got some major new impacts during the last two years. By comparing neutrino-electron scattering rates from Super-Kamiokande and first charged current results relying on inverse beta-decay from SNO it already became clear that active neutrino flavours besides ν_e are coming from the sun [10]. With the recent results on neutral current data and day/night effects in CC events, SNO was able to show, that indeed the dominant part of the solar

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neutrino flux is coming in a non ν_e flavour but the total flux is in agreement with standard solar model predictions [11]. Furthermore, to describe the data, the large mixing angle solution (LMA) is now in strong favour, having a best fit value of $\Delta m^2 = 5 \cdot 10^{-5} \text{ eV}^2$ and a mixing of $\tan^2 \theta = 0.34$ [12].

With these evidences in hand two goals emerge which can be explored by long baseline experiments, meaning a large distance of the detector from the neutrino source. First of all to prove the atmospheric and solar evidence and disentangle the oscillation channel using neutrinos from accelerators or nuclear power plants. The second goal is the fact, that we have to face a 3×3 mixing matrix among the neutrinos called MNS-matrix, in analogy to the CKM-matrix in the quark sector. It can be written in a convenient way as

$$\begin{pmatrix} \cos_{12} & \sin_{12} & 0 \\ -\sin_{12} & \cos_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos_{13} & 0 & \sin_{13} \\ 0 & 1 & 0 \\ -\sin_{13} e^{i\delta} & 0 & \cos_{13} e^{i\delta} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos_{23} & \sin_{23} \\ 0 & -\sin_{23} & \cos_{23} \end{pmatrix} \quad (2)$$

Ignoring the LSND result the first part could describe solar neutrinos, while the third one corresponds to atmospheric neutrinos. However, as can be seen from the part in the middle also CP-violation could in principle occur, requiring $\sin \theta_{13}$ to be non-zero. Therefore as a long term perspective, the measurements of all matrix elements together with a possible CP-violation and matter effects, which are at work in the Sun, could be explored. This is the goal for what is generally called "neutrino factories".

2 Reactor experiments

Reactor experiments are disappearance experiments looking for $\bar{\nu}_e \rightarrow \bar{\nu}_X$. Reactors are a source of MeV $\bar{\nu}_e$ due to the fission products being β -unstable. Experiments typically try to measure the positron spectrum, which can be deduced from the $\bar{\nu}_e$ - spectrum, and either compare it directly to the theoretical predictions or measure it at several distances from the reactor and search for spectral changes. Both types of experiments were done in the past. The detection reaction is

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad (3)$$

with an energy threshold of 1.804 MeV. Coincidence techniques are used between the annihilation photons and the neutrons which diffuse and thermalize within 10-100 μs . The reactions commonly used for neutron detection are $p(n, \gamma)D$ and $Gd(n, \gamma)Gd$ resulting in gamma rays of either 2.2 MeV or up to 8 MeV. The main background are cosmic ray muons producing neutrons in the surrounding of the detector.

With respect to past reactor searches, the recent experiments CHOOZ and Palo Verde can already be considered as long baseline experiments. Their distance to the power stations of 1030 m and about 800 m respectively is already a factor of at least three larger than any other reactor experiment done before. The results from CHOOZ [13] and Palo Verde [14] already exclude $\nu_\mu - \nu_e$ oscillations as

explanation for the atmospheric neutrino anomaly. Long-baseline experiments even by accelerator definitions will be done by KamLAND and BOREXINO. The KamLAND experiment [15] is installed in the Kamioka mine in Japan (Fig. 1). It contains 1000t of Liquid Scintillator as a main target, filled in a plastic balloon. Outside the balloon within a stainless steel sphere of 18 m diameter there is a mixture of paraffin oils. Together they form the inner detector. The readout is done with 1878 photomultipliers. The steel sphere is surrounded by buffer water with a total mass of 2500t. There are 6 reactors with a total thermal power of 69 GW in a distance between 140 km and 210 km to Kamioka which act as dominant $\bar{\nu}_e$ -source. They produce a total neutrino flux of $1 \cdot 10^6 \text{ cm}^{-2}\text{s}^{-1}$ at Kamioka for antineutrino energies larger than 1.8 MeV, resulting in 2 events/day. This will allow to measure Δm^2 below 10^{-5} eV^2 , therefore probing the LMA solution of the solar neutrino problem. If the background can be reduced by another factor of ten with respect to the proposed value, even the direct observation of solar ${}^7\text{Be}$ and terrestrial neutrinos seems feasible. Data taking started in January 2002.

Originally proposed for solar neutrino detection, also the BOREXINO experiment has the ability to investigate reactor neutrinos [16]. The $\bar{\nu}_e$ -flux at Gran Sasso Laboratory is around $1.5 \cdot 10^5 \text{ cm}^{-2}\text{s}^{-1}$ for energies larger than 1.8 MeV produced by power plants typically 800 km away. Without oscillation this would result in 27 events/year in a 300 t liquid scintillation detector. The sensitivity might go down to $\Delta m^2 \approx 10^{-6} \text{ eV}^2$ and $\sin^2 2\theta > 0.2$ (Fig. 1).

3 Accelerator experiments

This kind of long-baseline experiments focusses on the investigation of the atmospheric neutrino anomaly. Typical neutrino beams at accelerators are produced by protons hitting a fixed target, where the decaying secondaries (mostly pions) decay into ν_μ . This dominantly ν_μ beams are then used either for pure ν_μ -disappearance searches or for appearance searches by measuring electrons and/or τ -leptons produced via charged current (CC) reactions. The ν_τ -appearance search requires some beam design optimisation because the exploration of low Δm^2 values prefers lower beam energies but the τ -production cross-section shows a threshold behaviour starting at 3.5 GeV and is increasing with beam energy. A possible oscillation of ν_μ into sterile neutrinos might show up in the CC/NC ratio.

3.1 KEK- Super-Kamiokande

The first of the accelerator based long baseline experiments is the KEK-E362 experiment (K2K) [17] in Japan sending a neutrino beam from KEK to Super-Kamiokande. It is using two detectors, one about 300 m away from the target and Super-Kamiokande in a distance of about 250 km. The neutrino beam is produced by 12 GeV protons from the KEK-PS hitting an Al-target of $2\text{cm} \odot \times 65 \text{ cm}$. Using a decay tunnel of 200 m and a magnetic horn system for focussing

π^+ an almost pure ν_μ -beam is produced. The contamination of ν_e from μ and K-decay is of the order 1 %. The protons are extracted in a fast extraction mode allowing spills of a time width of 1.1 μ s every 2.2 seconds. With $6 \cdot 10^{12}$ pot (protons on target) per spill about $1 \cdot 10^{20}$ pots can be accumulated in 3 years. The average neutrino beam energy is 1.3 GeV, with a peak at about 1 GeV. The near detector consists of two parts, a 1 kt Water-Cerenkov detector and a fine grained detector. The water detector is implemented with 820 20" PMTs and its main goal is to allow a direct comparison with Super-Kamiokande events and to study systematic effects of this detection technique. The fine grained detector basically consists of four parts and should provide information on the neutrino beam profile as well as the energy distribution. First of all there are 20 layers of scintillating fiber trackers intersected with water. The position resolution of the fiber sheets is about 280 μ m and allows track reconstruction of charged particles and therefore the determination of the kinematics in the neutrino interaction. In addition to trigger counters there is a lead-glass counter and a muon detector. The 600 lead glass counters are used for measuring electrons and therefore to determine the ν_e beam contamination. The energy resolution is about 8% $/\sqrt{E}$. The muon chambers consist of 900 drift tubes and 12 iron plates. Muons generated in the water target via CC reactions can be reconstructed with a position resolution of 2.2 mm. The energy resolution is about 8-10 %. The detection method within Super-Kamiokande is identical to that of their atmospheric neutrino detection however precise timing cuts with the beam pulse can be applied. The low beam energy allows K2K only to perform a search for $\nu_\mu - \nu_e$ appearance and a general ν_μ -disappearance. The main background for the search in the electron channel is quasielastic π^0 -production in NC reactions, which can be significantly reduced by a cut on the electromagnetic energy. The proposed sensitivity regions are given by $\Delta m^2 > 2 \cdot 10^{-3} eV^2 (3 \cdot 10^{-3} eV^2)$ and $\sin^2 2\theta > 0.1 (0.4)$ for $\nu_\mu - \nu_e$ ($\nu_\mu - \nu_\tau$) oscillations, not completely covering the atmospheric parameters.

K2K has accumulated $5.6 \cdot 10^{19}$ pot, where the available results are based on $4.8 \cdot 10^{19}$ pot [18]. The number of observed events are shown in Tab.1. As can be seen, K2K observes a deficit with respect to expectation, however the number is in good agreement with the oscillation parameters deduced from the atmospheric data. If this ν_μ -disappearance is becoming statistically more significant, it will be an outstanding result.

3.2 Fermilab-Soudan

A neutrino program (NuMI) is also associated with the new Main Injector at Fermilab. The long baseline project will send a neutrino beam produced by 120 GeV protons to the Soudan mine about 730 km away from Fermilab. Here the MINOS experiment [19] is under construction. It consists of a 980t near detector located at Fermilab about 900 m away from a graphite target and a far detector at Soudan. The far detector will be made of 486 magnetized iron plates, producing an average toroidal magnetic field of 1.5 T. They have a thickness of 2.54 cm and an octagonal shape measuring 8 m across. They are interrupted by

about 25800 m² active detector planes in form of 4.1 cm wide solid scintillator strips with x and y readout to get the necessary tracking informations. Muons are identified as tracks transversing at least 5 steel plates, with a small number of hits per plane. The total mass of the detector will be 5.4 kt. The neutrino beam energy can be tuned by positioning the magnetic horn system in various positions relative to the target, resulting in different beam energies (Fig. 2). Oscillation searches in the $\nu_\mu - \nu_e$ and $\nu_\mu - \nu_\tau$ channel can be done in several ways. ν_μ disappearance searches can be performed by investigating the visible energy distributions in charged current events. A powerful way to search for oscillations is to compare the NC/CC ratio in the near and far detectors. By using this ratio, information on possible $\nu_\mu - \nu_{sterile}$ oscillations can be obtained, because $\nu_{sterile}$ would not contribute to the NC rate as well. A 10 kt-yr exposure will cover the full atmospheric evidence region. Start of data taking is foreseen around 2005.

3.3 CERN-Gran Sasso

A further program considered in Europe are long baseline experiments using a neutrino beam from CERN to Gran Sasso Laboratory [20]. The distance is 732 km. The beam protons from the SPS can be extracted with energies up to 400 GeV hitting a graphite target in a distance of 830 m to the SPS. After a magnetic horn system for focusing a decay pipe of 1000 m will follow. The average beam energy is around 20 GeV, optimized for ν_τ -appearance searches.

Two experiments are under consideration for the Gran Sasso Laboratory to perform an oscillation search. The first proposal is the ICARUS experiment [21]. This liquid Ar TPC with a modular design offers excellent energy and position resolution. A prototype of 600 t is approved for installation in Gran Sasso. An update with 2 additional modules of 1200 t each is planned. Beside a ν_μ - disappearance search by looking for a distortion in the energy spectra, also an ν_e - appearance search can be done because of the good electron identification capabilities. A ν_τ -appearance search can be obtained will be performed by using kinematical criteria as in NOMAD. For ICARUS a detailed analysis has been done for the $\tau \rightarrow e\nu\nu$ channel (Fig. 3) and is under investigation for other decay channels as well.

The second proposal is a ν_τ - appearance search with a 2 kt lead-emulsion sandwich detector (OPERA) [22]. The principle idea is to use a combination of 1mm lead plates as a massive target for neutrino interactions and two thin (50 μ m) emulsion sheets separated by 200 μ m, conceptually working as emulsion cloud chambers (ECC) (Fig. 4). The detector has a modular design, with a brick as basic building block, containing 56 Pb/emulsion sheets. 3264 bricks together with electronic trackers form a module. 24 modules will form a supermodule of about 652 t mass. Three supermodules interleaved with a muon spectrometer finally form the full detector. The total number of bricks is about 235000. The scanning of the emulsions is done by high speed automatic CCD microscopes. The τ , produced by CC reactions in the lead, can be investigated by two signatures. For long decays the emulsion sheets are used to verify the kink of the τ -decay,

while for short decays an impact parameter analysis can be performed identifying tracks not pointing towards the primary vertex point. The analysis here is done on an event by event basis. In five years of data taking, corresponding to $2.25 \cdot 10^{20}$ pot a total of 18 events are expected for $\Delta m^2 = 3.2 \cdot 10^{-3} eV^2$. Two further detectors basically designed for atmospheric neutrino detection, namely MONOLITH [23] and AQUA-RICH [24] could also be envisaged to be used in accelerator based oscillation searches.

4 Future machines

Driven by the recent evidences for oscillations and facing the three angles and one phase in the MNS-matrix, the idea to build new beams with very high intensity has been pushed forward.

4.1 Beta beams

The idea is to accelerate β -unstable isotopes [25] to energies of a few 100 MeV using ion accelerators like ISOLDE. This would give a clearly defined beam of ν_e or $\bar{\nu}_e$. Among the favoured isotopes discussed are ${}^6\text{He}$ in case of a $\bar{\nu}_e$ beam and ${}^{18}\text{Ne}$ in case of a ν_e beam.

4.2 Superbeams

Conventional neutrino beams in the GeV range run into systematics when investigating oscillations involving ν_μ and ν_e because of the beam contaminations of ν_e from K_{e3} decays. To reduce this component, lower energy beams with high intensity are proposed. A first realisation could be the JAERI-SK beam in Japan, in its first phase producing a 0.77 MW beam of protons with 50 GeV on a target and using Super-Kamiokande as the far detector [26]. This could be updated in a second phase to 4 MW and also a 1 Mt detector (Hyper-K). A similar idea exists at CERN to use the proposed SPL making a high intensity beam to Modane (130 km away). Such experiments would allow to measure $\sin^2 \theta_{23}$, Δm^2_{23} and might discover $\sin^2 \theta_{13}$.

4.3 Muon storage rings - neutrino factories

In recent years the idea to use muon storage rings to obtain high intensity neutrino beams was getting very popular [27]. Even many technical challenges have to be solved, it offers a unique source for future accelerator based neutrino physics. The two main advantages are the precisely known neutrino beam composition and the high intensity (about 10^{21} muons/year should be filled in the storage ring). A conceptional design is shown in Fig. 5. A first experimental step towards realisation is the HARP experiment at CERN, which will determine the target for optimal production of secondaries. Further experimental details are under study like muon scattering (MUSCAT experiment) or muon cooling

(MICE experiment), which has to be investigated as well. The storage ring itself could be constructed out of 2 straight sections connected by two arcs, where the straight regions are used as decay regions of the muons, producing neutrino beams in the corresponding directions. Besides options using existing baselines like CERN-Gran Sasso or Fermilab-Soudan, the possibility of observing matter effects and – because of the strong favour of the LMA solution in solar neutrinos – also CP violation, it might require even longer baselines of about 3000 km (Fig. 6) [28].

5 Summary and conclusions

The present evidences for neutrino oscillations and their description in theoretical models requires a variety of new experiments for detailed studies (Fig. 7). Long baseline experiments study the atmospheric anomaly using accelerators and the LMA solar solution with the help of nuclear power plants. First indications of ν_μ disappearance are already seen in K2K, the future activities of MINOS, ICARUS and OPERA will settle the question. KamLAND started data taking recently and will in the near future tell, whether LMA is indeed the correct solution as solar neutrino data suggest. Precise measurements of the MNS matrix elements, searching for matter effects and CP-violation would be under study using various new high intensity beams proposed.

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Table 1. Current results of K2K. Shown are total numbers observed within the fiducial volume of Super-Kamiokande as well as expected numbers for two scenarios, no oscillations and the best fit value of atmospheric neutrino anomaly. $\sin^2 2\theta = 1$ (after [17])

Super-K	Events	no oscillations	$\Delta m^2 = 3 \cdot 10^{-3} eV^2$
total	56	$80.6^{+7.3}_{-8.0}$	52.4
μ -like	30	44.0 ± 6.8	24.4
e - like	2	4.4 ± 1.7	3.7
multi ring	24	32.2 ± 5.3	24.3

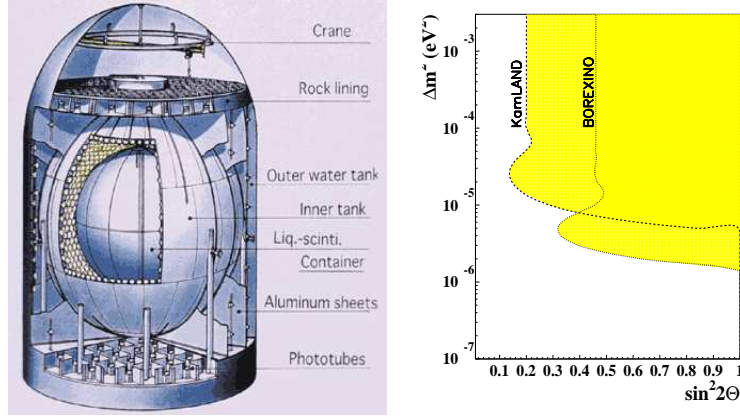


Fig. 1. Left: Schematic view of the KamLAND - detector, which started data taking recently. Right: Expected sensitivity curves for KamLAND and Borexino. The best fit value of the LMA solution is $\Delta m^2 = 5 \cdot 10^{-5} \text{ eV}^2$ (from [16]).

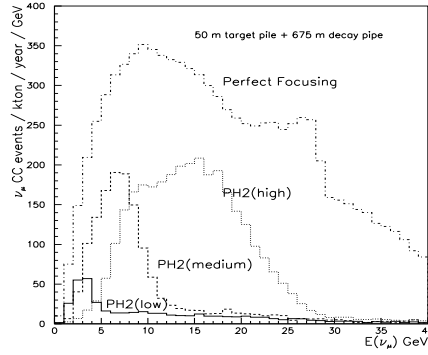


Fig. 2. The possible neutrino beam profiles discussed for NuMI. Motivated by the current Δm^2 preferred from atmospheric data, the PH2(low) beam option will be used.

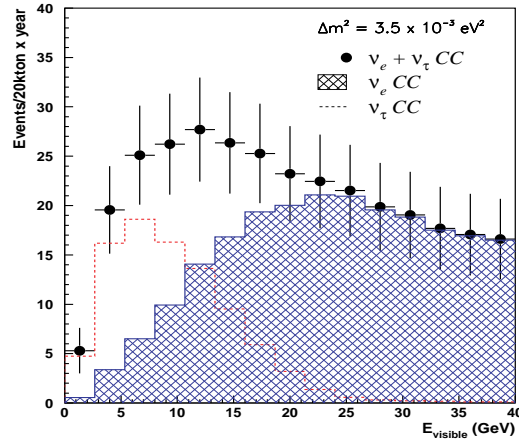


Fig. 3. Simulated visible energy distribution for ICARUS. The expected ν_e CC contribution is shown as filled histogram, the possible contribution of ν_τ CC with $\tau \rightarrow e\nu\nu$ at low visible energy is shown as dotted line. The points represents the combined curves including statistical errors.

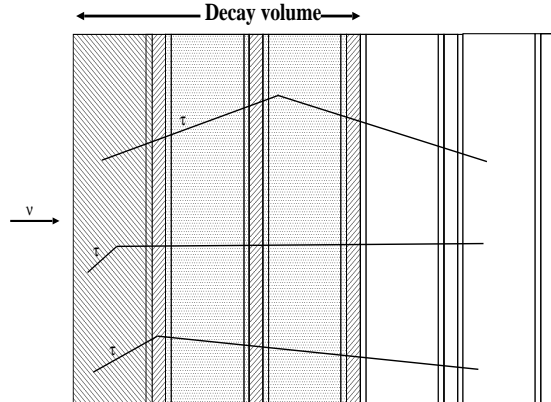


Fig. 4. Principal layout of an OPERA device working as an ECC. Thin emulsions sheet separated by a small gap are intersected by lead acting as target. The three different kind of expected topologies for τ -decays are shown.

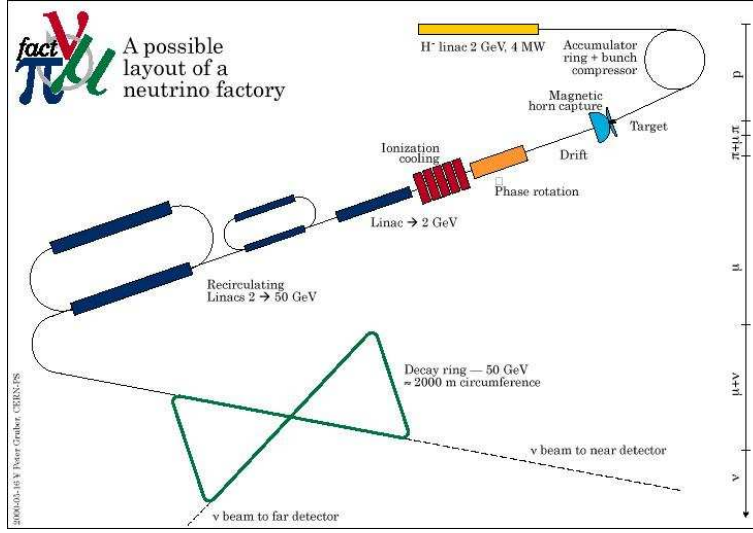


Fig. 5. Conceptual design of a neutrino factory discussed at CERN. A high intensity proton beam is hitting a target to produce secondaries. Myons from their decay will experience phase space cooling via ionisation loss, accelerated and finally brought into a storage ring. Possible design studies are also going on at BNL, Fermilab and RAL.

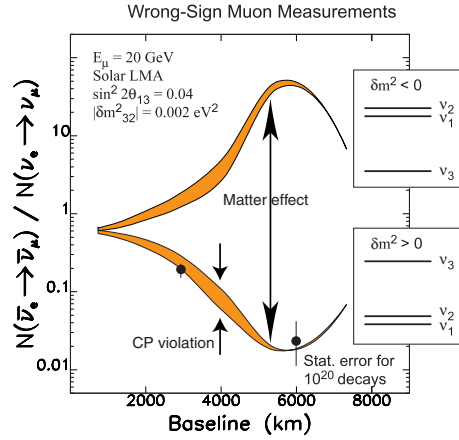


Fig. 6. Ratio of the number of wrong-sign muons using μ^- and μ^+ as beams. The two bands correspond to the sign of Δm_{23}^2 , the splitting shows the influence of possible matter effects and the width represents effects of a possible CP-violating phase.

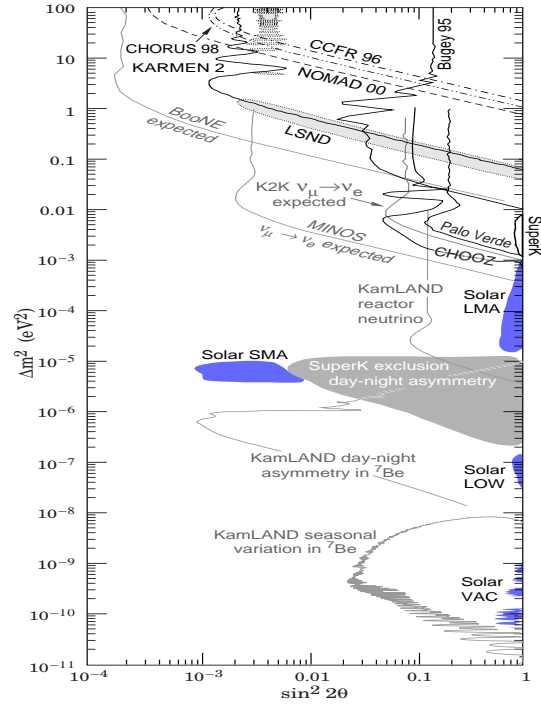


Fig. 7. Δm^2 - $\sin^2 2\theta$ plot of all current evidences for neutrino oscillations and proposed goals of various future experiments.